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# Picosecond laser cutting and drilling of thin flex glass

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ABSTRACT

We investigate the feasibility of cutting and drilling thin flex glass (TFG) substrates using a picosecond laser operating at wavelengths of 1030 nm, 515 nm and 343 nm. 50 µm and 100 µm thick AF32®Eco Thin Glass (Schott AG) sheets are used. The laser processing parameters such as the wavelength, pulse energy, pulse repetition frequency, scan speed and the number of laser passes which are necessary to perform through a cut or to drill a borehole in the TFG substrate are studied in detail. Our results show that the highest effective cutting speeds (220 mm/s for a 50 µm thick TFG substrate and 74 mm/s for a 100 µm thick TFG substrate) are obtained with the 1030 nm wavelength, whereas the 343 nm wavelength provides the best quality cuts. The 515 nm wavelength, meanwhile, can be used to provide relatively good laser cut quality with heat affected zones (HAZ) of $<25$ µm for 50 µm TFG and $<40$ µm for 100 µm TFG with cutting speeds of 100 mm/s and 28.5 mm/s, respectively. The 343 nm and 515 nm wavelengths can also be used for drilling micro-holes (with inlet diameters of $\leqslant$75 µm) in the 100 µm TFG substrate with speeds of up to 2 holes per second (using 343 nm) and 8 holes per second (using 515 nm). Optical microscope and SEM images of the cuts and micro-holes are presented.



## 1. Introduction

Glass as a substrate material has many benefits compared to other materials because of its excellent dielectric, chemical, mechanical and optical properties. Glass is transparent typically between 300 nm and 3.5 µm, durable to scratches and highly resistant to attack by acids, water, alkalis and organic substances. Therefore, it has found use in many applications, including optoelectronics (e.g. packaging and LCD displays) [1], telecommunication (e.g. optical fibres) [2], automotive components (e.g. windscreens) [3], lighting (e.g. OLED displays) [4], photovoltaics (e.g. solar cells) [5] and biotechnology (e.g. microfluidic devices) [6]. Recent developments in the glass manufacture sector have led to appearance of thin flex glass (TFG) in the market. The TFG materials, such as AF32® Eco Thin Glass (Schott AG) and Willow® Glass (Corning), have generated significant interest as a flexible substrate material for many of the aforementioned applications.

A wide range of (conventional and non-conventional) methods for cutting glass have been reviewed by Nisar et al. [7]. The conventional methods are based on scoring and snapping in which a diamond point or a wheel cutter is used for scribing and weakening the glass surface [8]. Later an external force is carefully applied to break the glass along the scribing path. Although this method is inexpensive, it does not provide general good surface finish of the cut edges and thus requires the use of additional mechanical processes, such as grinding and polishing, to make a smooth surface finish without cracks and chipping. This obviously increases the cutting cost and time [9].

The main non-conventional glass cutting methods are laser cutting [7], air-jet cutting [10] and hot water-jet cutting [11]. In contrast to the conventional cutting techniques these methods enable non-straight cuts in a single cutting step. The most common lasers used for cutting (cleaving) glass are $CO_2$ lasers, nanosecond pulsed solid-state lasers and ultra-short (picosecond and femtosecond) pulsed lasers [7,12,13]. However, other lasers such as high-power diode lasers [8], excimer lasers [14] or even hydrogen fluoride lasers [15] have also been demonstrated as tools for cutting glass. The relatively high absorption and low reflectivity of glass at the 10.6 µm wavelength means that $CO_2$ lasers are effective for cutting glass sheets with thicknesses of up 3 mm [7]. The thicker glass sheets, in turn, can be cleaved by nanosecond pulsed solid-state and high-power diode lasers because these provide higher optical penetration depth which results in homogenous heating across the material thickness [8]. Recently, it has been demonstrated that picosecond lasers are suitable for cutting chemically strengthened and tempered glass sheets with thicknesses between 100 µm and 10 mm [16]. This novel process, which is called the SmartCleave™ FI Technology, utilises an ultrashort pulse laser operating in a burst mode for the generation of a self-focused laser beam (also called laser filamentation [17])

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inside the glass. This process allows the glass sheets to be cleaved with very high speed (more than 300 mm/s) with no debris.

In addition to cutting and cleaving, lasers have also been demonstrated for micromachining, milling, surface polishing, texturing and modification, welding, scribing and drilling of glass [13,18–24]. They are particularly useful for drilling very small holes (with a diameter of $< 100\ \mu m$) in thin ($< 500\ \mu m$ thick) glass substrates which later can be used as interposers for high-density electrical interconnects in the electronic, optoelectronic and MEMS packaging applications. Recently, it has been demonstrated that both $CO_2$ and excimer lasers can be used for the generation of high-density through micro-holes in thin glass substrates [25–28]. Although $CO_2$ lasers enable the micro-holes to be generated in a relatively fast and inexpensive way (up to 4 holes per second in a 500 µm thick TFG [26]), the laser induced heating leads to the development of thermally induced stresses in the glass which then leads very often to material cracking. Therefore, it is necessary either to locally preheat the glass substrate before laser drilling or to perform a thermal post-treatment of the laser drilled glass [25]. These approaches, however, significantly reduce the effective drilling speed. Excimer lasers, meanwhile, provide the ability to produce crack-free micro-holes with an inlet diameter of $< 15\ \mu m$ [27], but the drilling speed is rather low (5 s needed to produce a micro-hole in a 100 µm thick TFG [27]). Although the drilling speed can be increased by using a mask projection system, as demonstrated by Delmdahl and Paetzel [28], the overall costs per hole are still high.

This paper examines the ability and efficiency of a picosecond laser for cutting thin flex glass (TFG), i.e., $\leq 100\ \mu m$ thick glass that cannot be successfully processed using the SmartCleave™ FI Technology process. The laser cutting experiments are carried out for three different laser wavelengths (1030 nm, 515 nm and 343 nm) and performed on 50 µm and 100 µm thick TFG (AF32® Eco Thin Glass) substrates. In this paper, picosecond laser drilling of micro-holes in TFG is also studied. The work described in this paper aimed to achieve cuts and vias with good surface quality (without microcracks and chipping) at the highest possible processing speeds.

## 2. Experimental

### 2.1. Laser setup

The laser setup used for cutting and drilling TFG substrates is presented in Fig. 1. The laser was a thin-disk TruMicro 5250-3C (Trumpf) laser that provides 6 ps laser pulses (FWHM) at three different wavelengths of 343 nm, 515 nm and 1030 nm. The maximum pulse energy generated by the laser at the fundamental wavelength (1030 nm) was 125 µJ, whereas the maximum pulse repetition frequency (PRF) was 400 kHz. The laser beam movement was controlled by a galvo scan head equipped with an F-theta focusing lens of focal length 160 mm.

The laser beam delivery to the workpiece (TFG) was similar for each wavelength. The output laser beam diameter was increased by a beam expander (BEX) in order to fill the input aperture of the galvo scan head ($\varphi_{IN}=14$ mm). The expanded laser beam was focused on the TFG using an F-theta focusing lens. The focused laser spot diameters were varied for each wavelength. The calculated focal diameters (at $1/e^2$ of the maximum intensity) were: 22.5 µm at $\lambda=1030$ nm, 14 µm at $\lambda=515$ nm and 10 µm at $\lambda=343$ nm. The quarter wave ($\lambda/4$) plate shown in Fig. 1 was used to obtain a circularly polarised beam with the 515 nm wavelength to investigate the impact of laser beam polarisation on TFG cutting and drilling performance. Laser processing of TFG substrates was carried out in air. The mounting arrangement for the glass provided a clear aperture underneath the machining region.

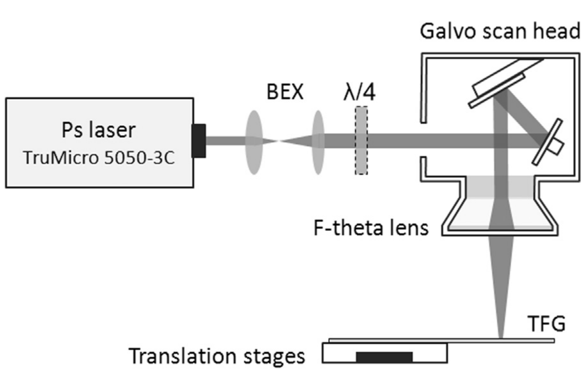


**Fig. 1.** Schematic of the laser setup.

### 2.2. TFG samples

50 µm and 100 µm thick AF32® Eco Thin Glass plates were used for the cutting and drilling experiments described in this paper. Prior to laser processing, the surfaces of the glass samples were gently cleaned using methanol, lens tissues and compressed air in order to remove any contamination and dust. A typical edge of the as-delivered 100 µm thick AF32® Eco Thin Glass substrate is shown in Fig. 2.

The AF32® Eco Thin Glass is a novel alkaline-free flat glass, manufactured by Schott AG, which has found use as a flexible substrate material for microelectronic, OLED lighting, display and photovoltaic applications [29]. This glass is produced by a down-draw method that enables production of glass sheets in a thickness range from 30 µm to 1.1 mm [30]. The AF32® Eco Thin Glass is naturally lightweight, flexible and rollable. Moreover, it is characterized by chemical strength and thermal stability, high scratch and scrub resistance, and certainly high optical transmission.

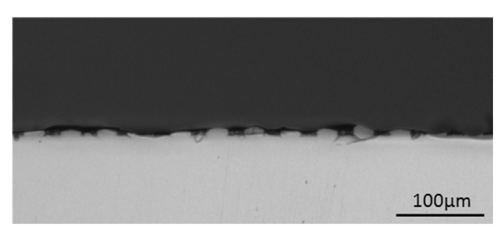


**Fig. 2.** Edge of the as-delivered 100 µm thick AF32® Eco Thin Glass substrate.

### 2.3. Experimental procedure

#### 2.3.1. Investigation of cutting performance for different wavelengths, pulse energies and pulse overlaps

The aim of these experiments was to find the optimum laser processing parameters, such as the laser wavelength ($\lambda$), pulse

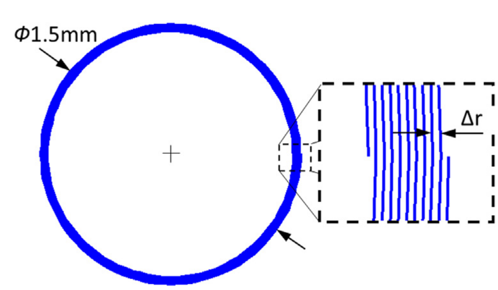


**Fig. 3.** Laser scan spiral track used for cutting the TFG substrate.

energy ($E_P$), pulse overlap ($o$), and number of laser passes ($N$), for high quality cutting without material cracking and chipping. The pulse overlap ($o$) was defined as follows:

$$o = \left(1 - \frac{v}{d \bullet PRF}\right) \bullet 100\% \quad (1)$$

where $v$ is the scanning speed, $d$ is the laser beam diameter used for cutting, and PRF is the pulse repetition frequency.

A circular cut with a diameter of 1.5 mm was chosen as a test cut. The experiments were carried out using pulse energies between 40 μJ and 105 μJ at $\lambda$=1030 nm, 25 μJ and 60 μJ at $\lambda$=515 nm, and 8 μJ and 24 μJ at $\lambda$=343 nm, limited in each case by the maximum available laser pulse energy at that wavelength. The PRF was fixed at 400 kHz. The maximum laser beam scan speed used for cutting was 2 m/s. This value was limited by the galvo scan head specification.

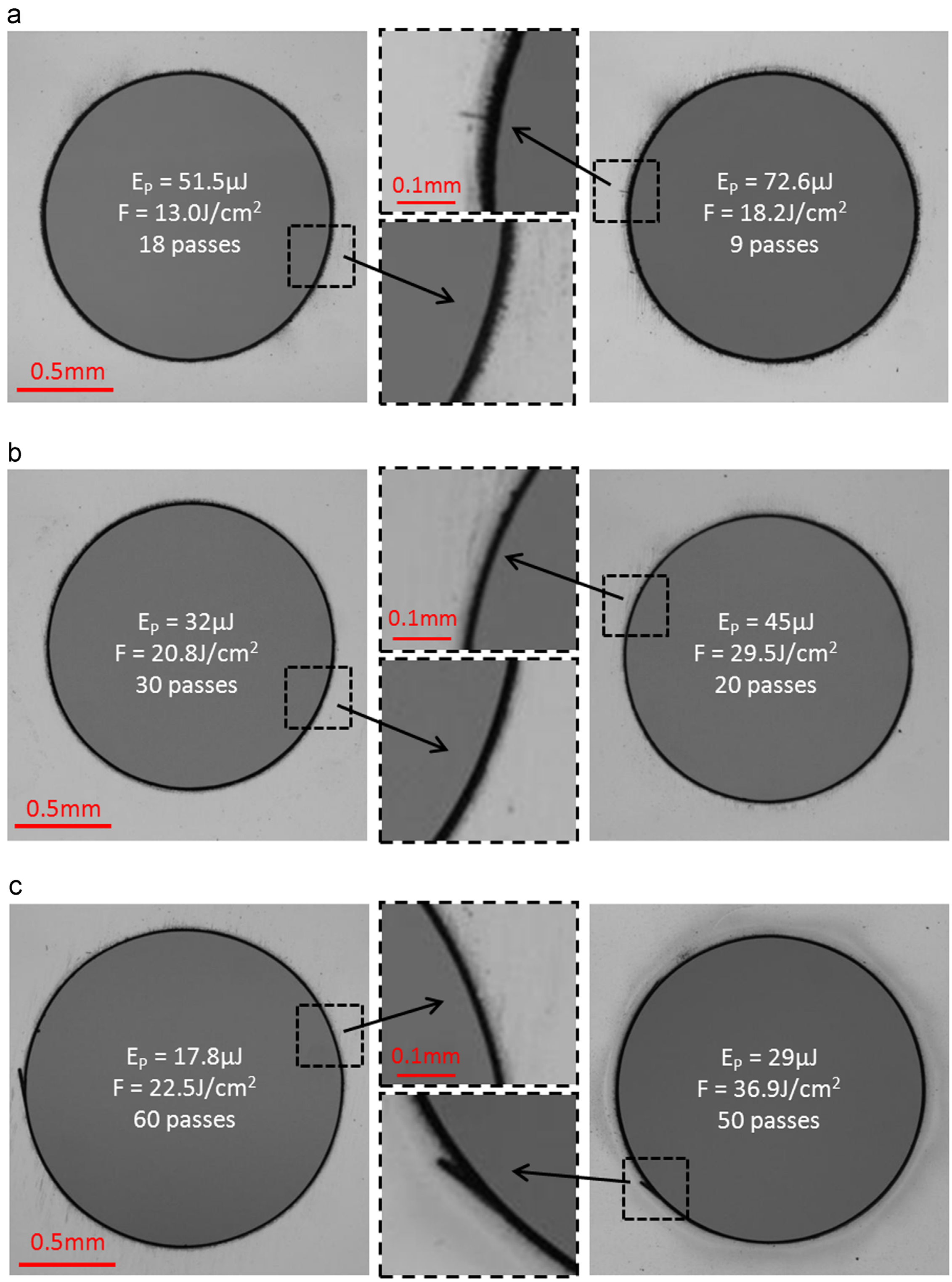


**Fig. 4.** Holes produced with laser wavelengths of: (a) 1030 nm, (b) 515 nm and (c) 343 nm in the 50 μm thick TFG substrate. Details of the pulse energy ($E_P$) and the number of laser passes are shown in the images. The PRF was 400 kHz and the scan speed was 2 m/s. A score near the edge of the holes in Fig. 4(c) results from a lack of proper calibration of the UV galvo scan-head (for so-called skywriting) at a 2 m/s scanning speed.

The effective cutting speed ($V_{EFF}$), expressed in the mm/s units, for three different laser wavelengths and two glass thicknesses was calculated using the following simple equation:

$$V_{EFF} = \frac{v}{N} \tag{2}$$

where $N$ is the number of laser passes required to generate a through cut in the glass substrate.

Initially, the galvo scan head was programmed to translate the focused laser beam along a circular track with a radius of 0.75 mm. This approach, however, had a serious drawback because the galvo scan head accelerated and decelerated the laser beam every single revolution. This led to overheating and the appearance of cracks around the laser-cut area due to an excessive thermal stress. To overcome this problem, the galvo scan head was programmed to translate the laser beam along a spiral track, as shown in Fig. 3. The spiral radius ($\Delta r$) was increased by 2 µm per revolution, ensuring multiple (typically 10) laser passes without stopping the laser beam. To cut through the TFG substrates it was necessary to run the galvo scan head program several times.

During the experiments, the glass substrate was visually inspected after every 10 laser passes. It was easy to determine the $N$ number because the circular off-cut detached when the glass substrate was completely cut through. The quality of the edges of the laser-cut holes was evaluated using an optical microscope (Leica DM6000 M).

*2.3.2. Laser drilling of micro-holes*

The 343 nm and 515 nm wavelengths were used for trepan drilling micro-holes of diameters $<80$ µm in the TFG substrates. The spacing between the micro-holes was chosen to be between 150 and 200 µm. The 1030 nm wavelength was not used for this task because at this wavelength the cutting results from the previous experiments were unsatisfactory.

The micro-holes were produced by translating the laser beam along the spiral track (see Fig. 3) in which an outer diameter ($\Phi$) was 30 µm, whilst the spiral radius increment (Δr) was 0.2 µm. The laser drilling of micro-holes was carried out with the scanning speed of 100 mm/s. The reduction of scanning speed from 2 m/s to 100 mm/s was necessary to maintain correct operation of the available galvo scan-head that coped poorly with high-speed movement of the laser beam between the 150–200 µm spaced areas selected for drilling. In order to maintain the pulse overlap of $<85\%$, which was found to be essential for cutting the TFG substrates without material cracking, the PRF was hence reduced from 400 kHz to 20 kHz.

The TFG substrates were drilled initially using a linearly polarised beam. However, given that polarisation has been reported to have a significant impact on laser scribing performance (Collins et al. [23]), a circularly polarised laser beam was also tested for comparison.

*2.3.3. Optimisation of laser processing parameters for cutting 100 µm TFG using 515 nm wavelength*

The good results obtained with the 515 nm wavelength in the experiments described in 2.3.1 encouraged us to exploit this wavelength to perform a range of cuts, i.e., straight and curved cuts, micro-holes, as well as larger holes of diameter $>1$ mm, in 100 µm thick AF32® Eco Thin Glass substrate. Different values of the pulse energy ($E_P$) and the scanning speeds ($v$) were tested to obtain the best quality cuts. The laser cut edges were analysed using the Leica optical microscope and a scanning electron microscope (FEI Quanta® 3D FEG).

## 3. Results and discussion

*3.1. Impact of laser wavelength and pulse energy on TFG cutting performance*

*3.1.1. 50 µm thick TFG substrate*

Through holes with a diameter of 1.5 mm were cut out in a 50 µm thick AF32® Eco Thin Glass substrate using 343 nm, 515 nm or 1030 nm wavelength. The laser operated with a PRF of 400 kHz. The laser scan speed was 2 m/s, corresponding to a pulse overlap of approximately 78% at $\lambda = 1030$ nm, 64% at $\lambda = 515$ nm and 50% at $\lambda = 343$ nm. The cutting was performed using a range of different pulse energies and numbers of laser passes.

Fig. 4 shows examples of through holes produced with all 3 wavelengths. The pulse energy and the number of laser passes required for cutting completely the glass substrate (i.e. without applying any mechanical force to detach the inner cut piece) are given on each figure. Based on these results, the effective cutting speed was calculated and is presented as a function of pulse energy and laser fluence in Fig. 5.

Fig. 5 shows that the highest effective cutting speed ($V_{EFF} \approx 220$ mm/s) is obtained with the 1030 nm wavelength and pulse energies $>70$ µJ. Unfortunately at this wavelength, the cutting quality is the poorest. Debris, re-deposited material as well as occasionally micro-cracks were observed within the HAZ (approximately 30 µm wide), as can be seen in Fig. 4(a). The best cut quality was obtained with the 343 nm wavelength, as shown in Fig. 4(c), with HAZ $<20$ µm and no micro-cracks or chipping. The

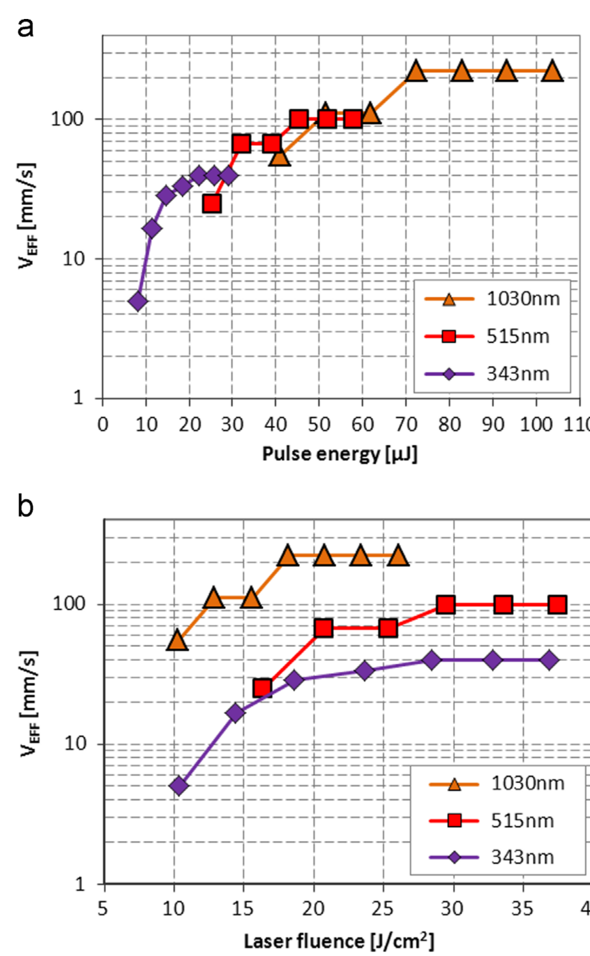


**Fig. 5.** Effective cutting speed ($V_{EFF}$) as a function of: (a) pulse energy and (b) laser fluence for the 50 µm thick AF32® Eco Thin Glass substrate. Results obtained for three wavelengths: 343 nm, 515 nm and 1030 nm.

drawback of this wavelength is the effective cutting speed which did not exceed 40 mm/s for the maximum laser pulse energy of 24 μJ. Good cutting results were also obtained with the 515 nm wavelength, as can be seen in Fig. 4(b). At this wavelength, the effective cutting speed was calculated to be 100 mm/s (when $E_P > 45$ μJ). The optical microscope images demonstrate that the laser-cut edges do not suffer from micro-cracks or chipping. The HAZ was measured to be less than 20 μm.

### 3.1.2. 100 μm thick TFG substrate

Through holes of diameter 1.5 mm were also cut out in a 100 μm thick AF32® Eco Thin Glass substrate, using all three laser wavelengths, with laser processing parameters identical to those listed in the previous section.

Fig. 6 shows that the 100 μm thick TFG substrate is more difficult to cut with a picosecond laser regardless of the wavelength used. For the holes cut with the fundamental laser wavelength

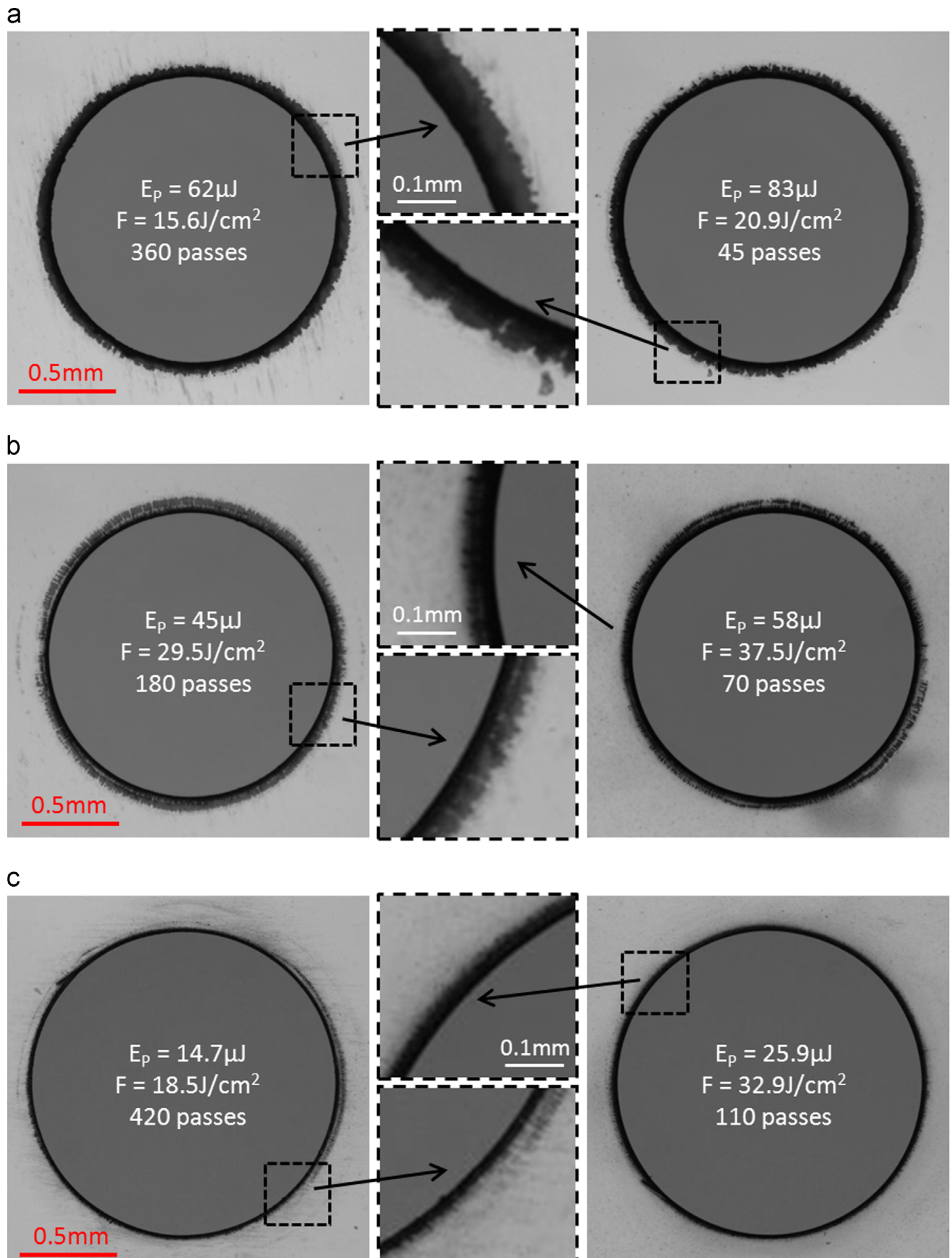


**Fig. 6.** Holes produced with laser wavelengths of: (a) 1030 nm, (b) 515 nm and (c) 343 nm in the 100 μm thick TFG substrate. Information about the pulse energy ($E_P$) and the number of laser passes is embedded into the images. The PRF was 400 kHz and the scan speed was 2 m/s.

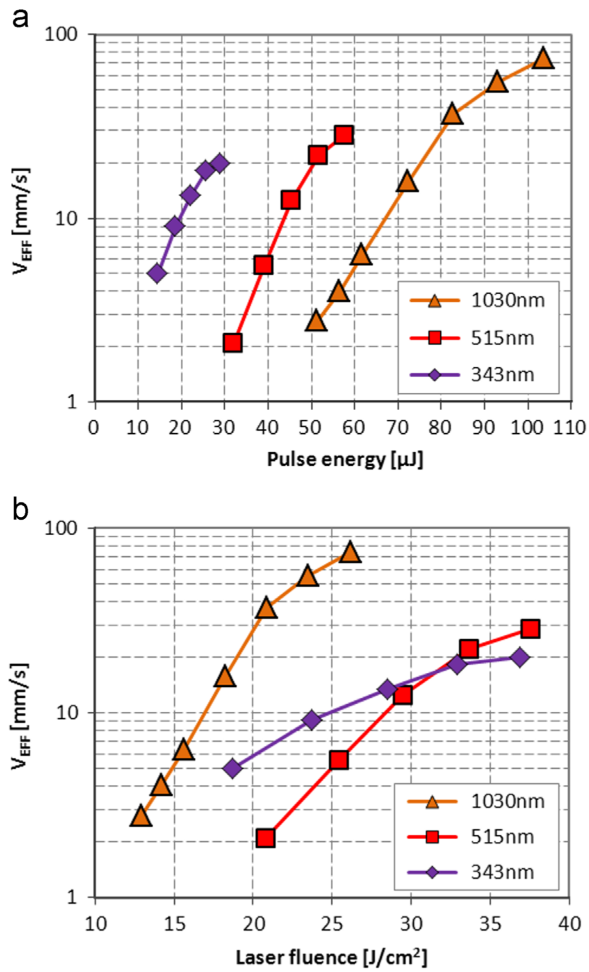


**Fig. 7.** Effective cutting speed ($V_{EFF}$) as a function of (a) pulse energy and (b) laser fluence for a 100 μm thick AF32® Eco Thin Glass substrate. Results obtained for three laser wavelengths: 343 nm, 515 nm and 1030 nm.

(1030 nm), as can be seen in Fig. 6(a), the holes were surrounded by both loose and firmly attached debris. In general, the HAZ was measured to be approximately 90 µm wide. The effective cutting speed at the maximum pulse energy of 104 µJ was calculated to be approximately 75 mm/s, as can be seen from the graphs in Fig. 7.

A smaller HAZ appeared around the holes produced with 515 nm and 343 nm wavelengths, as shown in Fig. 6(b) and (c), respectively. Using these wavelengths, no micro-cracks were observed and the re-deposited material was only partially embedded to the glass surface. Loose debris was removed by cleaning the laser-cut glass substrate in an acetone-filled ultrasonic bath. The effective cutting speed for the 515 nm wavelength was calculated to be 28.5 mm/s at the maximum pulse energy of 58 µJ. The best quality of laser cuts was obtained with the 343 nm wavelength. Unfortunately, the effective cutting speed at this wavelength was the lowest ($V_{EFF} \leq 20$ mm/s).

### 3.2. Impact of laser pulse overlap on TFG cutting performance

One of the laser processing parameters that has a significant impact on the cutting performance of TFG substrates is a pulse overlap ($o$). This is demonstrated in Fig. 8 with a 100 µm thick AF32® Eco Thin Glass sample which was cut using a laser wavelength of 1030 nm, laser spot of 22.5 µm, pulse energy of 104 µJ and PRF of 400 kHz. The cutting was performed with different laser scan speeds ($v$), and hence with different pulse overlaps. The key results, which are presented in Fig. 8, show that too large a pulse overlap (see Fig. 8(a) and (b)) leads to significant material cracking, whereas a pulse overlap of 77.8% (see Fig. 8(c) and (d)) provides satisfactory cutting without damaging the glass substrate.

A low scan speed means that the pulse overlap is high. The residual heat generated during the ablation process by subsequent laser pulses accumulates along the scan track due to insufficient time for heat loss by conduction through the glass [31] and the laser-induced thermal stresses lead to the material cracking. The residual heat can be reduced by decreasing the PRF and/or increasing the scan speed. If the pulse overlap is too small, however, the ablation rate is reduced and thus more laser passes have

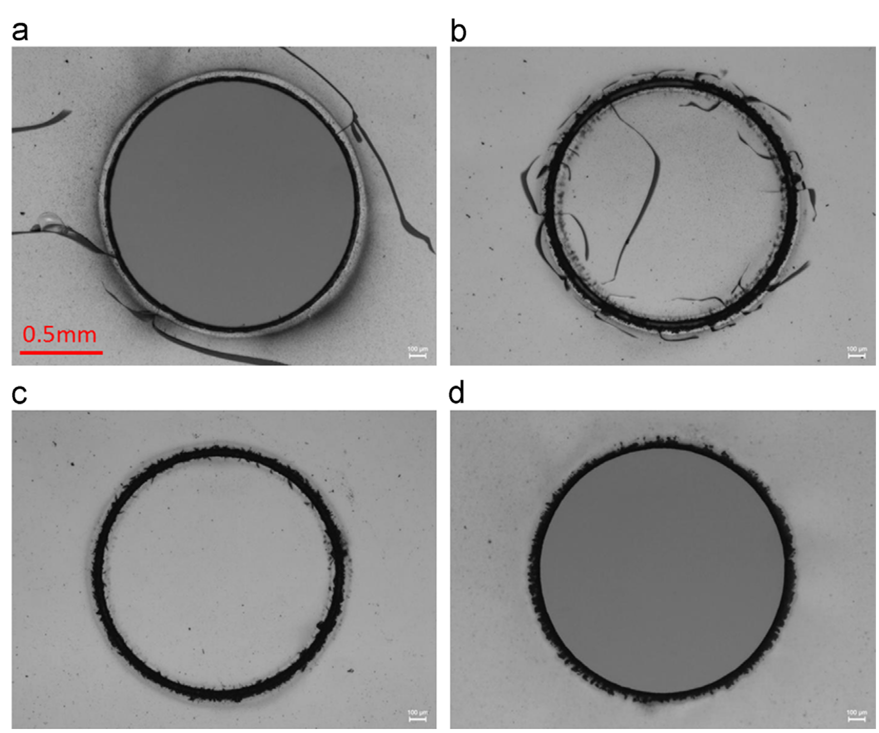


**Fig. 8.** 1.5 mm diameter holes in a 100 μm thick AF32® Eco Thin Glass, demonstrating the impact of pulse overlap on induced cracking. The cutting speed ($v$), pulse overlap ($o$) and the number of laser passes ($N$) required to generate a through cut were as follows: (a) $v$=0.4 m/s, $o$=95.5% and $N$=9, (b) $v$=1 m/s, $o$=88.9% and $N$=9, (c) $v$=2 m/s, $o$=77.8% and $N$=9 and (d) $v$=2 m/s, $o$=77.8% and $N$=27. The laser wavelength used was 1030 nm.

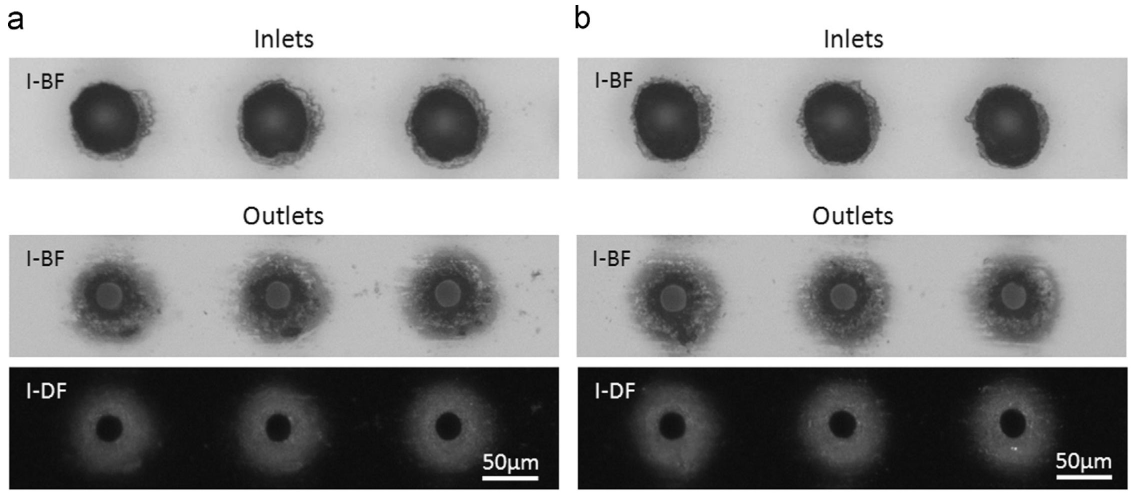


**Fig. 9.** Micro-holes produced in the 100 µm thick TFG substrate using 515 nm wavelength and either (a) linearly-polarised or (b) circularly polarised beam. The laser processing parameters were as follows: $E_P$=66 µJ, PRF=20 kHz, $v$=100 mm/s, and $N$=125 passes. The images were captured using the Leica optical microscope operating in the incident bright-field (I-BF) and the incident dark-field (I-DF) mode.

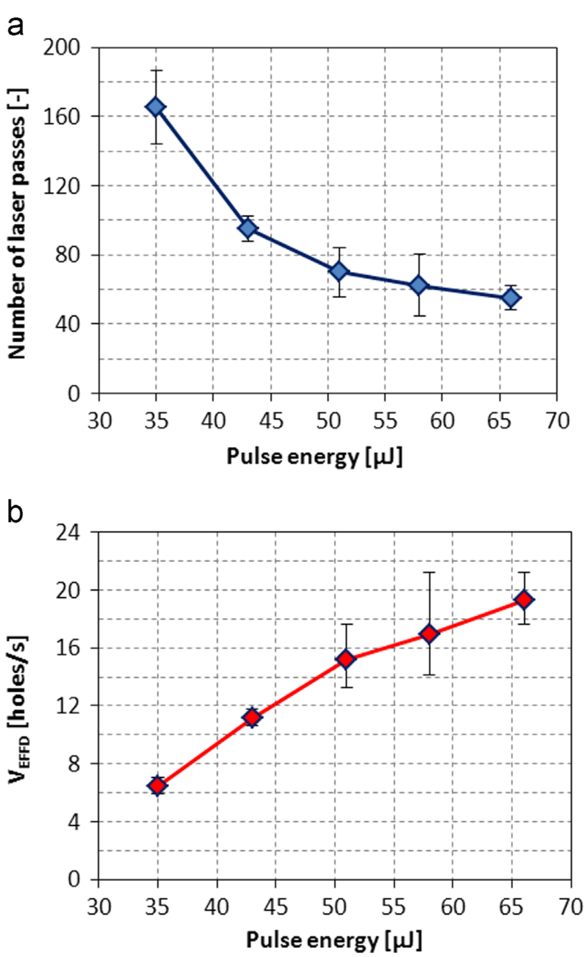


**Fig. 10.** (a) The number of laser passes required to drill through the 100 µm TFG substrate and (b) the calculated effective drilling speed ($V_{EFFD}$) as a function of the pulse energy.

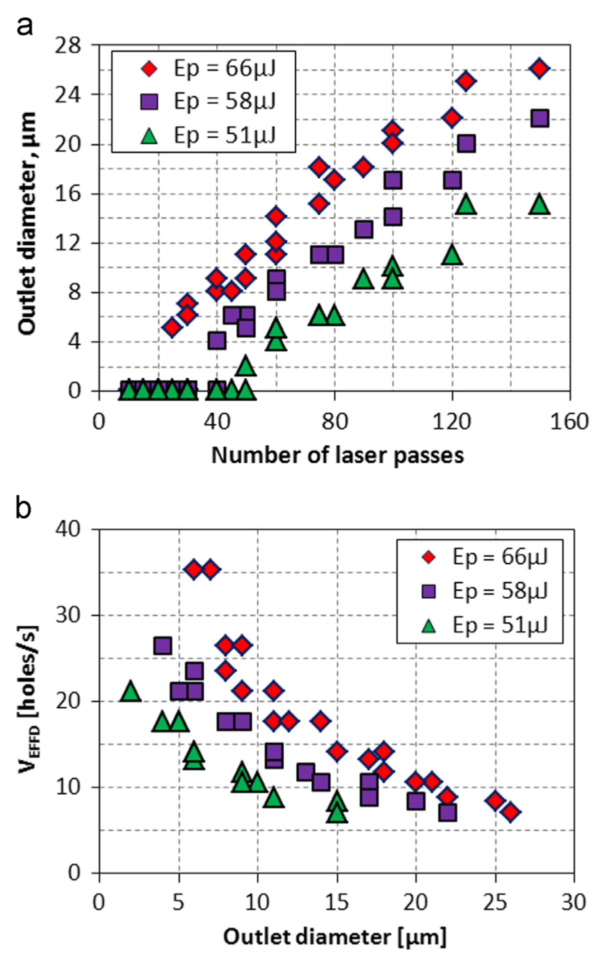


**Fig. 11.** (a) Micro-hole outlet diameter as a function of the number of laser passes for $E_p$=51 µJ, 58 µJ and 66 µJ. (b) The calculated effective drilling speed ($V_{EFFD}$) as a function of the micro-hole outlet diameter.

to be used to remove a given volume of the material, for instance 27 laser passes are required in Fig. 8(d).

In general, it was found that the TFG substrates can be successfully cut with a picosecond laser, i.e., without cracking of glass, when the pulse overlap is less than 85%, independently on the laser wavelength used.

### 3.3. Laser-drilling of micro-holes

#### 3.3.1. 515 nm wavelength

Micro-holes can be successfully produced using a 515 nm wavelength. Fig. 9 shows micro-holes that were produced by either: (a) linearly polarised or (b) circularly polarised laser beam, translating the beam along the spiral track (see Fig. 3) of an outer diameter 30 μm. 125 laser passes were used to produce such micro-holes. The other laser processing parameters were as follows: $E_P$=66 μJ, PRF=20 kHz, $v$=100 mm/s. In general, no significant difference was observed between the micro-holes produced by the laser beams of different polarisation.

Fig. 10(a) shows that a 100 μm thick AF32® Eco Thin Glass substrate can be drilled through by using approximately 55 laser passes at $E_P$=66 μJ. This means that it is possible to produce 20 micro-holes with an inlet diameter of 60 μm within 1 s, as can be seen in Fig. 10(b). The effective drilling speed ($V_{EFFD}$) was calculated as follows:

$$V_{EFFD} = \frac{v}{N * (2\pi r)} \quad (3)$$

where $v$ is the scan speed, $N$ is the number of laser passes and r is the outer radius of the spiral track as shown in Fig. 3. Eq. (3) defines the maximum number of micro-holes that can be produced within 1 s because it does not include the time to move the laser beam between holes.

The diameter of the micro-hole outlets depends on the number of laser passes and the pulse energy used, as shown in Fig. 11(a). For pulse energies of 51 μJ, 58 μJ and 66 μJ, it was found that the diameter of the outlets increases almost linearly with increasing number of laser passes. The maximum diameter of the outlets was measured to be approximately 26 μm, obtained for $N$=150 passes and $E_P$=66 μJ. Here, it must be noted that the increased number of laser passes does not affect the diameter of the inlets. In general, the laser-drilled micro-holes are tapered. The smallest taper angle of the micro-holes produced on a 100 μm thick TFG substrate was estimated to be 8.5°. This number corresponds to the inlet diameter of 55 μm and the outlet diameter of 25 μm.

Based on the results presented in Fig. 11(a), the effective drilling speed obtained for drilling through micro-holes with a specific outlet diameter in a 100 μm thick TFG substrate can be calculated. Fig. 11(b) shows that approximately 8 micro-holes with an outlet diameter of 25 μm can be produced within 1 s.

#### 3.3.2. 343 nm wavelength

Fig. 12 shows an array of 60 μm diameter micro-holes which were produced in a 100 μm thick TFG substrate using a linearly polarised laser beam of the 343 nm wavelength. The micro-holes were produced with $E_P$=35.6 μJ, PRF=20 kHz and $v$=100 mm/s, translating the focused laser beam many times along the spiral track (see Fig. 3) of an outer diameter 30 μm. The micro-hole outlet diameter was found to be approximately 20 μm when 240 laser passes were used (see Fig. 12(a)), and 35 μm when the number of laser passes was increased to 600 (see Fig. 12(b)). The HAZ around the micro-holes was <20 μm. Using Eq. (3) it was calculated that micro-holes such as those shown in Fig. 12(b) can be produced within 0.6 s. Thus the effective drilling speed with the 343 nm laser wavelength is significantly lower than that obtained with the 515 nm wavelength.

### 3.4. Optimisation of laser cutting parameters for 515 nm wavelength

The cutting results presented in Section 3.1 show that high quality laser-cut edges can be obtained in 50 μm thick TFG using multiple passes of the 515 nm wavelength, with an effective cutting speed of 100 mm/s. With the 100 μm thick TFG substrate, however, the quality of cuts is poorer, with noticeable HAZ and debris. Here we demonstrate that high quality cuts in 100 μm TFG can be obtained by using a higher pulse overlap, lower pulse energy and fewer laser passes. In this approach, however, it is necessary to use a small breaking force following laser processing

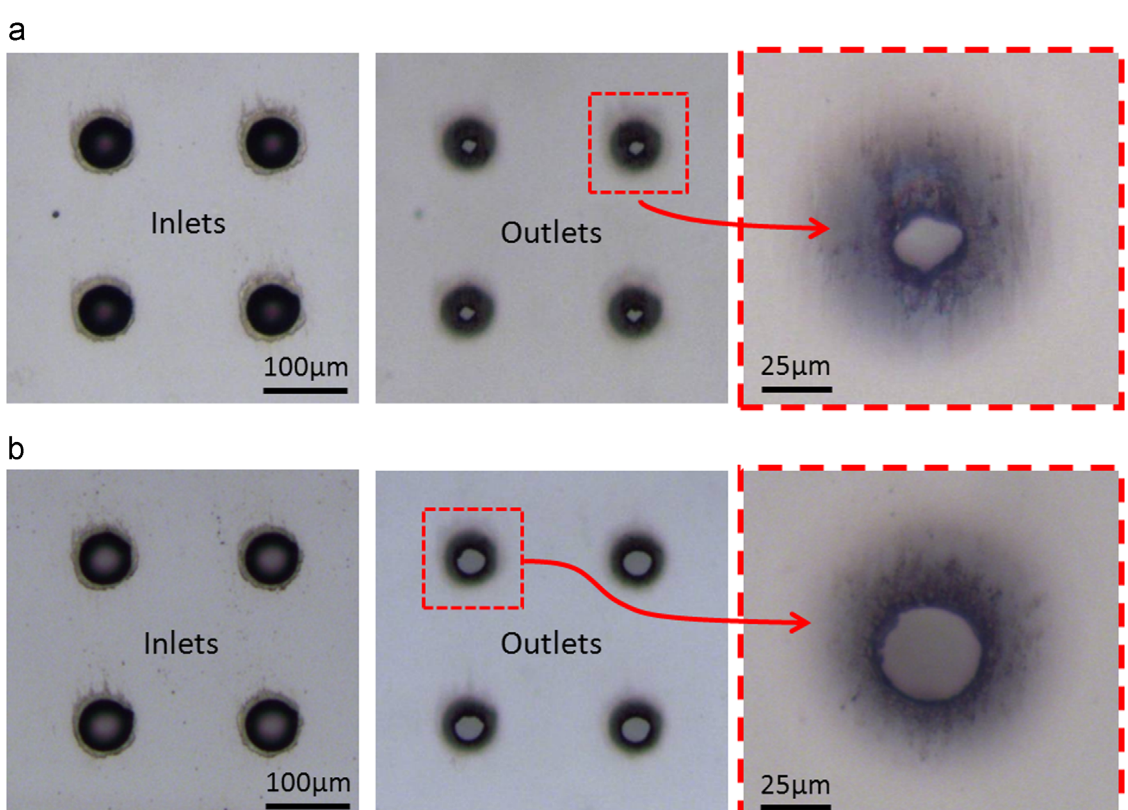


**Fig. 12.** An array of micro-holes produced in the 100 μm thick TFG substrate using 343 nm wavelength. To produce the micro-holes, the number of laser passes ($N$) was: (a) 240 and (b) 600. The other laser processing parameters were as follows: $E_P$=35.6 μJ, $v$=100 mm/s and PRF=20 kHz.

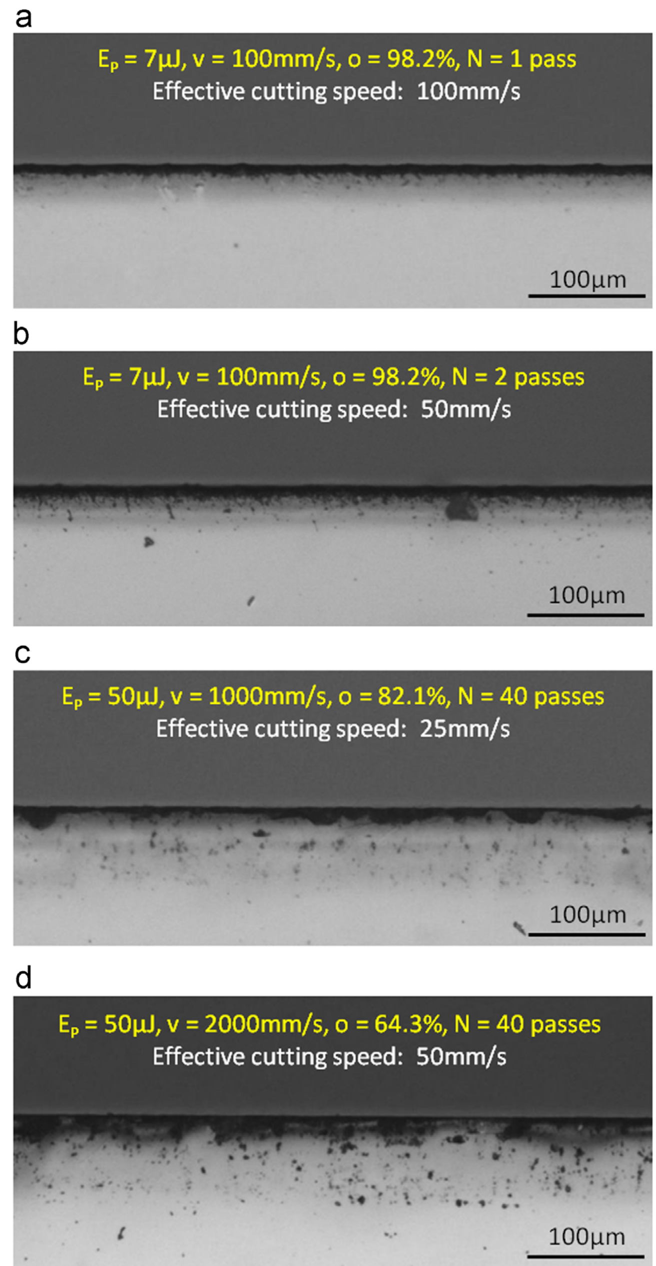


**Fig. 13.** Straight cuts performed on a 100 μm thick TFG substrate using a 515 nm wavelength. The pulse energy ($E_P$), scan speed ($v$), pulse overlap ($o$) and number of laser passes ($N$) used for making straight cuts are given in each image. The PRF was 400 kHz.

in order to snap a TFG substrate along the laser-scribed line. The main drawback of this 'scribe and break' method is that it is effective only for cutting straight lines. More complex cuts, such as curved and wavy lines, are not possible because TFG easily undergoes uncontrolled fractures while an external breaking force is applied.

Fig. 13(a) shows that a very clean edge can be produced with a single laser pass using 7 μJ pulse energy and 98.2% pulse overlap. However, these processing parameters are not sufficient to cut completely the 100 μm thick TFG substrate by the laser. This edge, like also the other shown in Fig. 13(b), was produced by a two-step process, i.e., the laser scribing and snapping approach [7]. Fig. 13(b) shows that subsequent laser passes can increase HAZ and cause chipping. As discussed in Section 3.2, this effect is associated with excessive thermal accumulation. Fig. 13(c) shows the edge of the glass substrate which was cut using 50 μJ pulse energy and 1 m/s scan speed. By increasing the pulse energy and scan speed, and hence decreasing the pulse overlap from 98% to 82%, it was possible to cut through the 100 μm thick TFG substrate, using only the laser radiation, without causing serious damage to the material. However, it was not possible to produce clean edges with no chipping. The chips were in the range of 10-20 μm. By comparing Fig. 13(c) with Fig. 13(d), it can be concluded that a pulse overlap of between 80% and 85% is optimum for cutting through the 100 μm thick TFG substrates.

### 3.5. Demonstration of the picosecond laser cutting process on 100 μm thick TFG

Fig. 14(a) shows an example of the structure that was cut out of a 100 μm thick AF32®Eco Thin Glass substrate using a circularly-polarised beam of wavelength 515 nm. Fig. 14 shows also a close-up of the laser-cut areas highlighted in Fig. 14(a) – see dashed squares.

The inner large hole of diameter 4 mm and the outer (straight and curved) cuts were performed using the following laser processing parameters: $E_P$=52 μJ, $v$=1 m/s and PRF=400 kHz. The pulse overlap was 82.1%. To cut out the 4 mm diameter hole it was necessary to use 32 laser passes in order to detach the inner off-cut, whilst to perform the outer cuts, i.e., straight and curved lines, the number of passes was increased to 36. This number of laser passes was sufficient to detach the off-cuts without applying any breaking force.

The inner holes of diameter 1 mm and the micro-holes of diameter 75 μm were produced with a 100 mm/s scan speed. The lower scan speed was necessary to ensure correct operation of the galvo scan head for drilling such small holes. The pulse energy was again 52 μJ. To cut 1 mm diameter holes the laser operated with a 40 kHz PRF, providing the pulse overlap of 82.1%. Each hole was cut by translating the laser beam along a spiral track similar to that shown in Fig. 3. The spiral had an outer diameter of 1 mm, an inner diameter of 0.96 mm, whilst a radius increment ($\Delta r$) was 2 μm per revolution, providing 10 laser passes in the spiral pattern. The laser beam movement along the spiral track was repeated 5 times in order to perform a through cut in the TFG substrate. The above laser processing parameters and approach were found to be optimum to ensure small HAZ and little debris around the cut region, as can be seen in Fig. 14(d). The 20 kHz PRF was used for drilling 75 μm diameter micro-holes. The micro-holes were produced by translating the laser beam 5 times along a spiral track, similar to that shown in Fig. 3, in which the outer diameter was 48 μm, the inner diameter was 40 μm, whereas the $\Delta r$ was 0.2 μm per revolution. Such an approach enables the generation of micro-holes with an outlet diameter of 30 μm, as shown in Fig. 14(g).

The total time required to perform all cuts in the 100 μm thick TFG substrate, including drilling the micro-holes, was measured to be 34 s. As shown in Fig. 14, the quality of the laser cuts is relatively good. Hence, it can be concluded that a picosecond laser can be successfully used for cutting and drilling TFG substrates.

## 4. Conclusions

The use of a picosecond laser for cutting and drilling TFG substrates of thicknesses 50 μm and 100 μm was investigated, providing a successful approach for processing these attractive materials. The laser processing parameters such as the wavelength, pulse energy, pulse overlap and number of laser passes, which are necessary to perform a through cut or to drill borehole

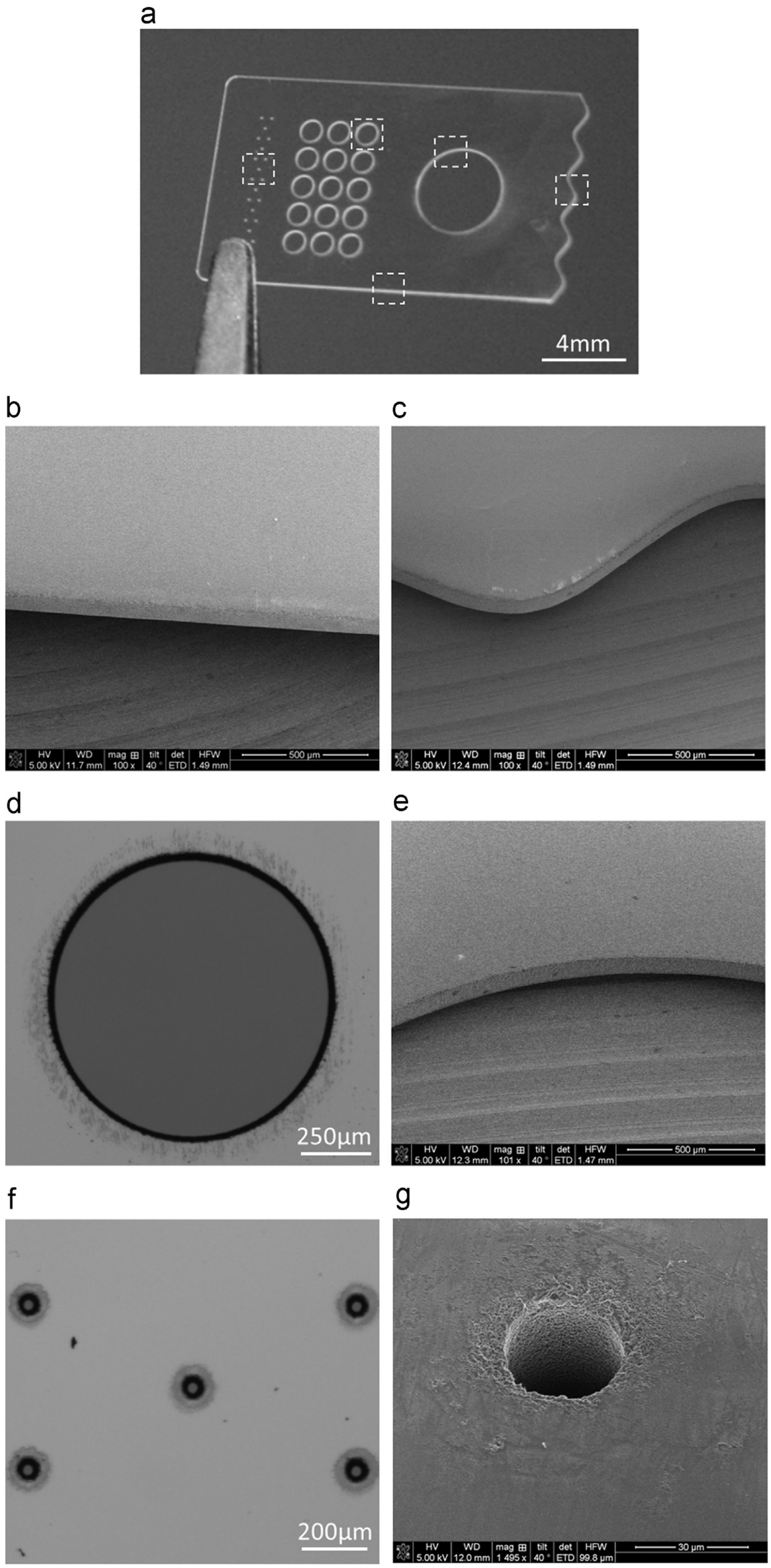


**Fig. 14.** (a) An example of the laser-cut structure in a 100 μm thick AF32® Eco thin Glass substrate. This figure also shows a close-up of: (b) straight cut (SEM image), (c) curved cut (SEM image), (d) 1 mm diameter hole (optical microscope image), (e) 4 mm diameter hole (SEM image), (f) 75 μm diameter micro-holes (optical microscope image) and (g) micro-hole outlet (SEM image).

in a TFG substrate, were examined in detail. It was shown that the highest effective cutting speed can be obtained with the wavelength of 1030 nm, but the quality of the laser cuts at this wavelength is rather poor. The best cutting results were obtained with the wavelength of 343 nm; however, the cutting speed was the lowest. The experiments performed with the 515 nm wavelength revealed that the 50 µm and 100 µm thick TFG substrates can be cut with the laser scan speeds of 100 mm/s and 28.5 mm/s, respectively. At this wavelength, the quality of the laser cuts was good, with HAZ $<25$ µm and little debris.

In this paper, we also demonstrated that the picosecond laser pulses of wavelengths 343 nm and 515 nm can be used for drilling micro-holes in a 100 µm thick TFG substrate. The maximum drilling speeds were measured to be approximately 2 micro-holes per second for 343 nm and 8 micro-holes per second for 515 nm. The optical microscope and SEM analysis showed that the micro-holes are surrounded by a relatively small HAZ and little debris. Our future work will focus on optimisation of laser processing parameters for drilling 100 µm thick TFG substrates, which is a more challenging task than laser drilling of 50 µm TFG.

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